SYSTEMÖKOLOGIE ETHZ

SYSTEMS ECOLOGY ETHZ

BERICHT/REPORT Nr. 34

March 2011

Courseware «World Model 2»

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Update and translation of "Unterrichtsprogramm «Weltmodell 2»" by Fischlin, A., T. Blanke, D. Gyalistras, M. Baltensweiler & M. Ulrich, 1991, Systems Ecology Report No. 1

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Recommended citation:

FISCHLIN, A. & M. M. FISCHLIN-KISSLING, 2011. *Courseware «World Model 2». Update and translation of "Unterrichtsprogramm «Weltmodell 2»" by Fischlin, A., T. Blanke, D. Gyalistras, M. Baltensweiler & M. Ulrich, 1991 (Systems Ecology Report No. 1).* Systems Ecology Report No. 34, Institute of Integrative Biology (IBZ), ETH Zurich, Zurich, Switzerland, 41pp. http://www.sysecol.ethz.ch/publications/reports#34

Limits to Growth and Courseware «World Model 2»

Updated and Translated by

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Based on
Unterrichtsprogramm «Weltmodell 2»
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Daddy Daddy, it was just like you said,
now that the living outnumber the dead[1].

by Laurie Anderson

from song
“Speak my language”
from album
“Bright Red”

[1] This statement is actually only true if one counts the dead only since A.D. 1500. The latter are roughly a bit more than 6 billions and as of this writing there are more than 6.971 billion (10^9) humans alive today. Rough estimates of accumulated dead humans in billions (10^9) are: 10 since A.D. 1000, 16 since A.D. 0, and 95 assuming modern man exists since about 60’000 years.

1. Introduction

This courseware serves as an introductory example to familiarise oneself with the basic concepts of modelling, analysis and simulation of complex dynamic systems by dealing with fundamental problems associated with the growth of the human population known by the phrase "Limits to Growth" or with the words of the Club of Rome “the problématique”.

1.1 Theme and purpose of the courseware

Many of us have limited experience in dealing with complex systems such as nonlinear dynamic systems and often consider this to be a bewildering and baffling experience. Such difficulties are inextricably linked with the characteristics of complex dynamic systems and particularly large when we try to correctly predict the behaviour of such systems or to steer them in a desired direction. This courseware is dedicated to such a system, i.e. the worldwide interdependencies that regulate the fate of the human population.

At least for the last 1000 years the human population of the Earth has increased without constraints following a hyperexponential growth (Fig. 1, see also Varfolomeyev & Gurevich, 2001).

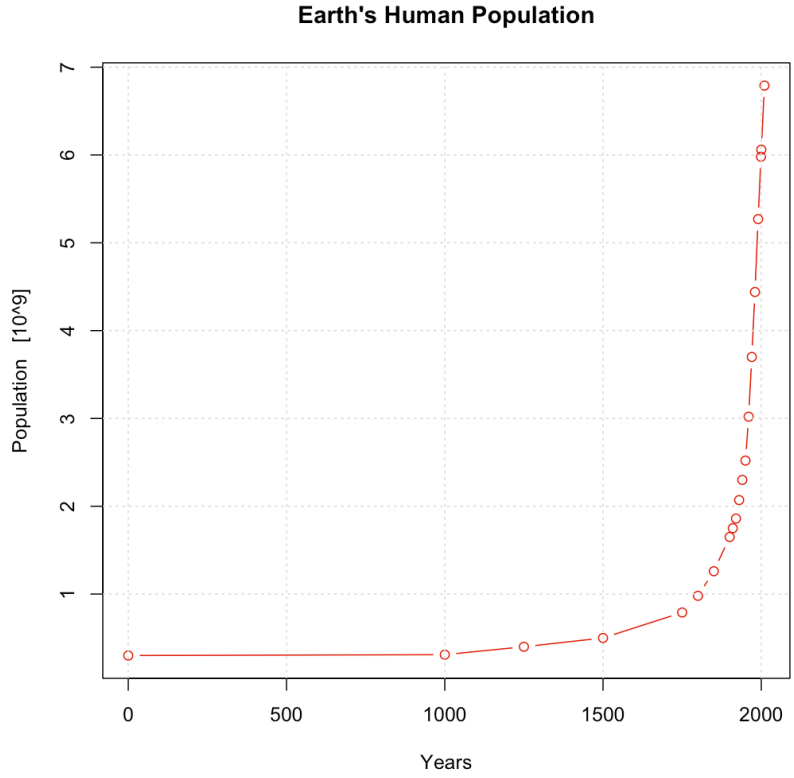

Fig. 1: Development of the world population (United Nations, 2011).

This led on our globe to special conditions, in particular in the last decades, which are unique in mankind’s history: A tiny disturbance or impact on the environment typically resulting from ordinary daily activities, seemingly minor and negligible from the perspective of an individual human being, can grow to enormous implications, first at the regional, later at the global scale (see also Jacobi, 1987). An example from developing countries: The demand for firewood needed for cooking resulted in some regions of the Sahel (Africa) in a total clearance of all trees and shrubs within a radius of up to 100 km from human settlements (Barney et al., 1980 (Global 2000); Southwick, 1985). This affects the local climate with concomitant adverse impacts on agriculture. Even economical consequences result, so that for example the urban population is forced to spend on average, approximately one third of their income for the purchase of wood (Southwick, 1985). An example from developed countries: The combustion of fossil fuels for industrial production, transport and habitation has

significantly contributed to an increase in atmospheric carbon dioxide of roughly 40% compared to preindustrial conditions. According to many projections using climate models, this will lead to global climate change with likely undesirable impacts (Clark, 1982; Dickinson & Cicerone, 1986; Schneider, 1989; IPCC, 2007).

However, this is not the place to really look into all these problems in detail. Rather we intend to show that there exist important linkages between diverse aspects i.e. between population size, agriculture, industrial activities, and the environment, that form a complex net of interdependencies, which can hardly be understood without special means[2]. Yet, the effect of these interdependencies onto the fate of the human population may be not only crucial, but may also bring surprises, such as a population collapse (see below). Surprises often arise when changes within a certain period can only be detected by precise quantitative measurements, yet the accumulated effect of those causes in the end a drastic qualitative change. The latter is then only too often perceived as a complete surprise. For example, a complete crop failure or the extinction of entire societies due to drought has probably resulted from just a small quantitative change in climatic conditions causing e.g. precipitation decreases that rippled through society till an entire civilization collapsed (e.g. Weiss & Bradley, 2001; Lucero, 2002; Diamond, 2009). To be able to study such phenomena, e.g. for the purpose of forecasting, prevention or mitigation, we need a suitable approach overcoming the limitations of the human mind in understanding the dynamics of a complex system (e.g. Dörner, 1997). An important goal of systems analysis is to provide techniques and methods, in particular modelling and simulation, which enable us humans to better understand complex systems.

The courseware program *World Model 2* is such a tool. It tries to capture world affairs, especially the fate of the human population, in terms of the processes economic growth, consumption, agriculture and pollution (Forrester, 1971, 1972). The model is grossly simplistic, but it is a noteworthy attempt and, by the way, also the first one of its kind, to address such relationships at the global scale. Beginning in the year 1900 the model first simulates the past and then calculates the future development of the world population, the economy, agriculture, the consumed non-renewable resources, plus environmental pollution till the end of the 21st century.

A more refined successor of this model, "World model3", has garnered worldwide fame. At the New York Stock Exchange the price of gold suddenly jumped upwards, and a wave of consternation and concern seized the mass media throughout the industrialized world. All caused merely by the publication of the book «The limits to growth: a report for the Club of Rome's Project on the Predicament of Mankind» (Meadows et al., 1972; Meadows & Meadows, 1976). The book written in a popular language described the findings of Dennis Meadows' (a former student of J.W. Forrester) team, including the simulation results of the aforementioned model. The book became a bestseller across the world and was translated into innumerable languages. The projections for this century were perceived as a dark future for mankind, namely a catastrophic population collapse in the 2nd half of the 21st century. Several simulations indicated that this collapse would be inevitable if no fundamental change in policies should take place and human kind would maintain its current course.

This courseware comes with the learning or courseware program *World model 2*. It permits to intervene by changing policies and thereby to steer the course of humankind towards a better future. Selected model parameters can e.g. boost the economy, the efficiency of resource use, enhance environmental protection or introduce birth control. The program then calculates the fate of mankind under the conditions as changed by the user by calculating population size and other variables such as material standard of living, food supply, or the quality of life. The user should try to influence the model in such a manner that the devastating population collapse in the 21st century is avoided.

Although the model represents a coarse simplification of the world, the attempts to steer the world towards a more desirable course is far from trivial. Here system theory may help. It deals among other things not only with the necessary mathematical methods to represent complex systems in form of models and to simulate their behaviour, but also to search systematically for possibilities to control such complex systems. In particular solutions are of special interest that optimize certain aspects of the system. Important properties of complex model systems, such as their sensitivity to built-in assumptions or to changes in parameters that can be estimated only with limited accuracy (**sensitivity analysis**) can only be studied using sound analytical methods. This includes the identification of equilibria and their stability properties (**stability analysis**).

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2 J.W. Forrester, the father of system dynamics, said in this context: "Thus we ... have an enormeous wealth of exquisite information available on the parts of the system, yet no useful approach... to predict reliably the system's behavior, ... so that different people draw different conclusions from the same input factors. Often accepted conclusions are in conflict with accepted assumptions, and such discrepancies go a long time unnoticed, since the systems are so complex that the human mind is not capable to relate properly the multitude of causes with the multitude of possible consequences." (Oltmans, 1974, p.12).

1.2 Educational goal

Getting to know a dynamic, nonlinear and complex system and first exposure to systems analytical approaches. Experiencing that the behaviour of a complex system is often difficult to predict and may contrast with the expectations. Experiencing the difficulty to steer the behaviour of a complex system in a desired direction and learning to accomplish a control only through considering and respecting the system's internal dynamics.

1.3 System requirements of the courseware program (hard- and software)

The learning program here called courseware program was written in Modula-2 (MacMETH[3]) with the modelling and simulation software "ModelWorks"[4] (version 2.0 or later) based on the "DialogMachine"[5] (version 2.0 or later) and runs on any Apple Macintosh[6] or Windows machine. The program is designed as an independent application ("double-clickable") and requires only standard system Software[7] (details in Annex III). It may be useful to record certain simulations on paper, but the educational goal does not require students to have access to a printer.

2. Theory

2.1 General

Models, especially mathematical models are central to understanding complex systems. They are important because they enable us to learn about inaccessible or to improve our understanding of hardly accessible characteristics of the real system they are modelled after. This is particularly relevant for the investigation of environmental systems. E.g., a forecast can of course never be carried out experimentally. Or to estimate the impact of a new agrochemical on human health and the environment, the substance is first tested on a small model system before it is applied at larger scales, let alone worldwide. Which test pilot would board the plane unless he or she is assured that a model of this plane has proven to be able to fly? Or a certain variable cannot be measured directly, but can be computed from other measurements under the assumption a particular model is valid. E.g. a limnologist cannot measure directly the primary production of a lake. However, through the increase of oxygen or the respective decrease of carbon dioxide from the lake water kept for some time in a pair of bottles[8], one exposed to light, the other not, makes it possible to measure primary productivity assuming the stoichiometry of photosynthesis holds (Vollenweider, 1974). For these and similar reasons scientists and engineers build often first a model and investigate it in place of the real system they built the model after. With digital computers it became possible to solve very complex models by executing so called **simulation experiments**. Consequently in recent decades modelling and simulation has become popular in almost all scientific fields, in particular to many it has been previously absent. To the basic methodology of science, i.e. theory and experiment, has been added a third pillar: simulation.

Models always differ from the systems they are modelled after, otherwise we would not build them. Typically **models are simpler than their original** (real system). Given a specific problem at hand, the model is built to exhibit only those properties that are of interest in that given context. Others system characteristics can and should be neglected as much as possible (parsimony, Occam's razor). This means, however, that any results derived by means of only the model must not be transferred back to the original without caution. In principle model results apply only to those aspects of the original, which have been represented adequately in the model. E.g. the *World model 2* is a gross simplification compared to its original, the real world. On the other hand it

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6 With at least 1 Kbyte RAM[6] (random access memory) and 128 Kbytes ROM (read only memory)

7 starting with Finder version 5.3 or Windows 95

8 A pair of samples of lake water is kept in a so-called light and dark bottle of glass. The former bottle allows for photosynthesis by the entrapped algae, the latter bottle enclosed in aluminum foil allows for respiration only under otherwise identical conditions.

focuses on the human population and attempts to consider well the major factors influencing this population. Note, that one distinguishes different model categories: There are **physical models** such as the toy train or the wind tunnel. There are **conceptual models,** such as the Rutherford or the Bohr-Sommerfeld atomic model, and there are **mathematical models**, such as a system of coupled non-linear differential equations as this is the case with the *World model 2*.

Systems consist of system elements and relationships between these elements. **System elements** can be grouped according to their particular mathematical properties into following types: input variables, state variables, auxiliary variables, output variables and model parameters. For example, the *World model 2* knows following five **state variables** (Fig. 2):

Population	P
Natural Resources	NR
Capital Investment	CI
Pollution	POL
Capital Investment in Agriculture Fraction	CIAF

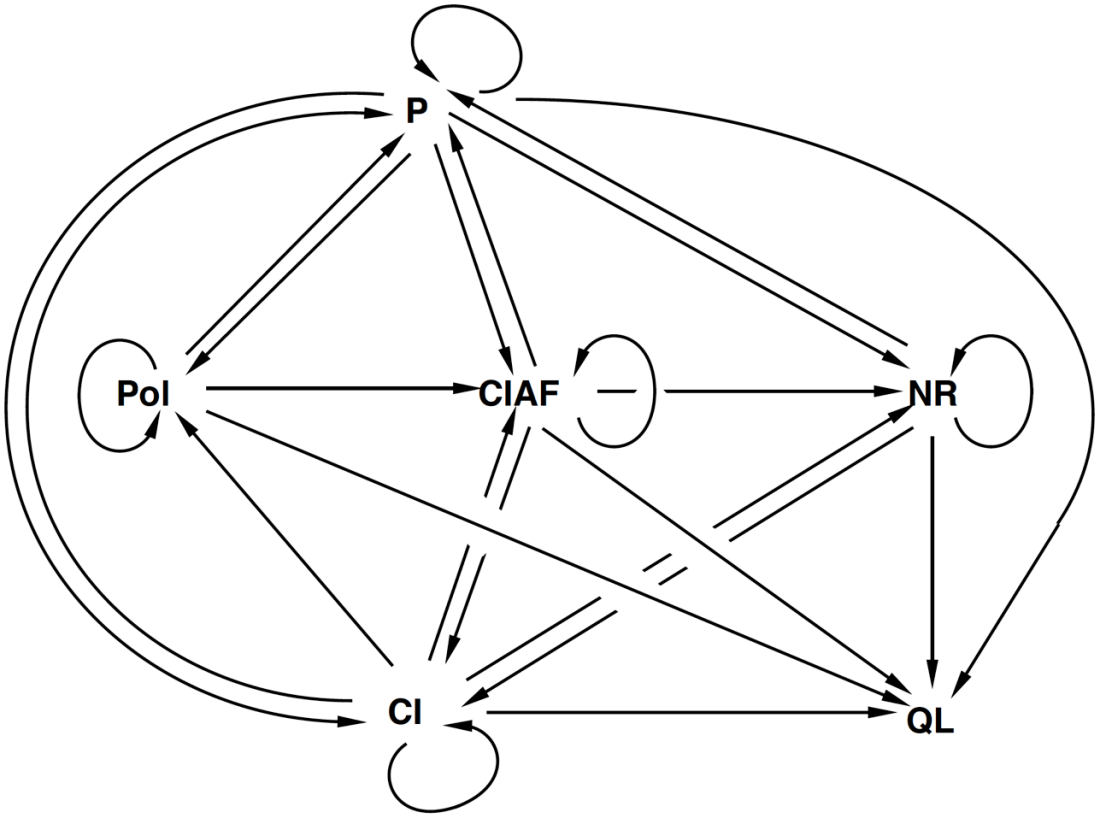

Fig. 2: Relational graph of «World model 2» by Forrester (1971, 1972). P – Human population (world); Pol – Pollution; CIAF - Capital Investment in Agriculture Fraction; NR - Natural Resources (non-renewable resources); CI - Capital Investment; QL - Quality of Life. → : Influences between system elements.

The **output variable** Quality of Life QL (Fig. 2) is of particular interest among the many outputs of the *World model 2* . There are no **input variables** such as temperature, which would influence the world dynamics. This means that the model system is autonomous and e.g. climate change effects are by definition excluded. However, there is a large number of **auxiliary variables**, e.g. the material standard of living or food ratio, and a many **model parameters**.

The **relationships** between the system elements determine the **system structure**, which can be very complex. For example natural resources affect the human birth rate indirectly through influencing the capital investment, the food production, the pollution and the existing land surface in an extremely complicated manner (Fig. 2; see also Forrester, 1971, 1972). The arrows symbolize influences of particular system elements on other system

elements. Such relationships typically represent the dependency of the temporal derivation of a state variable from other system elements, whether that may be other state variables, inputs or model parameters. The «World model 2" is therefore a **dynamic model**, and describes phenomena such as population increase or decrease, economic growth or decrease, the consumption of natural resources or increase and the decrease of environmental pollution. All relationships together form the so-called system structure and are described in form of mathematical equations Many models are formulated as systems of coupled ordinary differential equations, which is also the case for *World model 2* .

State variables and **model parameters** are particularly important. For example in the Worldmodel, the actual human birth rate B_R varies as an auxiliary variable, measured in number of births per capita per year in function of other variables such as the auxiliary variable material standard of living (m(t)). This variable influence results from following calculation:

$$B_R(t) = B_{RN} * m(t) \qquad t \text{ continuous time or } t \in \Re \leftarrow \qquad (1)$$

B_{RN} (Birth Rate Normal) is a model parameter, which typically is a constant as long as certain assumptions remain valid, which may be the case for the duration of a finite period, e.g. from 1900 till 2100. Many modifying factors influence then this birth rate as follows:, E.g. the material standard of living is assumed to have normally the value 1. However, system influences may cause this value to become larger, i.e. a value higher than 1, Otherwise they may cause the value to become smaller, i.e. a value smaller than 1 If multiplied with the standard birth rate normal (equation (1)) the deviation within the material standard of living influences thus the number of births.

The **normal value**, e.g. the value of the model parameter B_{RN}, is determined by relatively fixed biological properties of the human species and cultural values and behaviours. Therefore, model parameters are not necessary constant for all times, but they may change their values as assumptions are relaxed or strengthened. For example, some culture may rate having a large number of children a blessing. Spreading such value systems worldwide, would of course require to increase the parameter B_{RN} accordingly.

Since the temporal behaviour of a system is not only determined by the form of the equations, but also by the parameter values, a surprisingly large spectrum of model behaviours may result alone from changes in its parameter values. To explain or predict such effects is a typical task of systems theory. Under certain circumstances it may be possible to turn the behaviour of a system completely around by a mere modification of parameter values, so that the new behaviour meets some human expectations or needs much better.

2.2 Specific background

The focus of the "World model 2» is on the **world population**,, which has been growing hyper-exponentially (Fig. 1, Tab. 1), a phenomenon often termed “population explosion”.

Year	Millions
-10'000	10
0001	300
1650	510
1700	625

Year	Millions
1750	710
1800	910
1850	1’130
1900	1’600

Year	Millions
1930	2’070
1950	2’510
1960	3'020
1970	3’575

Year	Millions
1980	4'440
1990	5'270
2000	6'060
2010	6’790

Tab. 1: World population in million humans from 10'000 BC. to 1987 (Lane *et al*., 1986; United Nations, 2011).

The purpose of the model is to project the development of mankind in the near future till the end of this century. It considers a set of critical variables, which may change during the course of these years. Thus the model contains state and auxiliary variables that influence not only the human population, but that may also influence each other. Together they represent the current world situation as it determines the fate of humanity. Neither the inter-dependence of direct and indirect influences, nor the derivation of the model equations can be meaningfully summarized here[9], for this they are simply too complex. Know that the team of Professor Jay W.

9 All elements used in the model, their meaning, units and equations are tabulated in the Annex

Forrester who built the model at MIT[10] consisted of scientists from various disciplines. Despite its relative simplicity does the model consider cleverly and quite elegantly many more aspects of the real world than one might think at first glance. To fully appreciate the model, the interested reader is referred to the original literature (Forrester, 1971, 1972; Meadows et al., 1973; Meadows & Meadows, 1976).

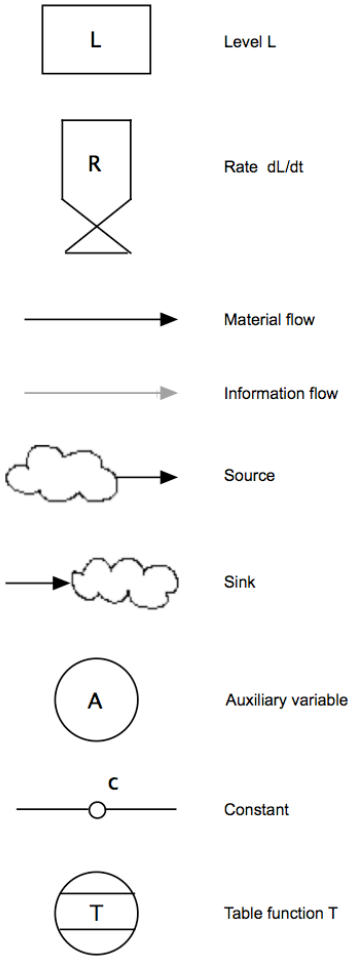

Fig. 3: Symbols used in a Forrester signal flow diagram (Forrester, 1968).

During the 2nd half of the 1950s Forrester has developed a methodology to model and simulate any kind of dynamic system an approach especially targeted at economic and social phenomena. This approach is called **System Dynamics** and is characterized by the fact that the modeller starts modelling by drawing a graph, a so-called Forrester signal flow diagram (see e.g. Fig. 4, 5, 6 and Fig. 13 in the Annex). System elements are represented by specific symbols (Fig. 3) named in a manner unique to the approach.

For example, instead of the widely used term state variable, Forrester uses the term **Level**. The time derivative of a state variable is typically split into an additive and a subtractive term, the so-called **rates**. The sum of those two terms then forming an ordinary, first order **differential equation**. If we take population size x(t) and its time derivative $\dot{x}(t) = dx(t)/dt$ as the difference between births rate B and death rate D, we get the following differential equation:

$$\dot{x}(t) = dx(t)/dt = B(x(t) - D(x(t)) \qquad (2)$$

The corresponding Forrester signal flow diagram is shown in Fig. 4.

10 Massachusetts Institute of Technology

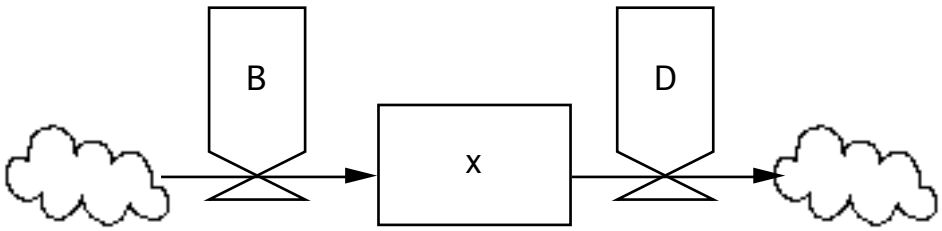

Fig. 4: Forrester signal flow diagram used for a graphical representation of the differential equation $\dot{x} = B - D$.

The birth rate *B* determines the amount of inflow from the source to the level variable *x* and enters the differential equation as a positive (additive) term. The death rate rate *D* determines the outflow from the level variable *x* to the sink and enters the differential equation as a negative additive term. This Forrester signal flow diagram assumes there is some material flow going from the source into the level and then out from the level to the sink. The inflow into the level being "regulated" by the rate *B*. the outflow from the level being "regulated" by the rate *D* (note the valve like symbol used for rates).

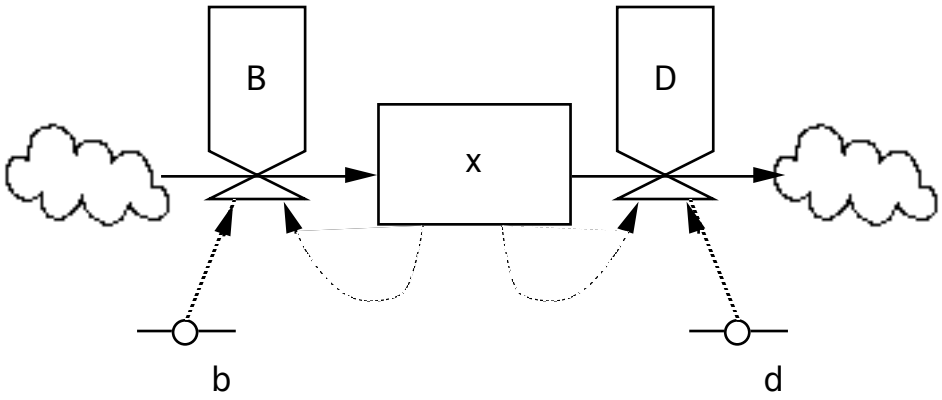

Fig. 5: Forrester signal flow diagram of the differential equation $\dot{x} = bx - dx$ to describe the increases and decreases in human population *x* or *x(t)*, the level variable or state variable. Shown are two feedback loops in addition to the material flow through the level (compare Fig. 4). The rates $B(t) = bx$ and $D(t) = -dx$ are the birth and death rates determining inflow and outflow of the level variable *x*. Both rates are time dependent, just as *x*, whereas the constants *b* and *d* are time-independent model parameters. The process is time continuous, i.e. the time $t \in \Re$.

The next step is to find those elements that determine the number of births and deaths, i.e. the birth and death rate respectively. It is certainly safe to assume that both the births and deaths increase with the number of people and vice versa. Therefore, as a first approximation, we can assume that both the birth and the death rate are directly proportional to the current population size x:

$$\dot{x}(t) = dx(t)/dt = b \cdot x(t) - d \cdot x(t) \qquad (3)$$

The birth rate *B* becomes $b \cdot x$ and the death rate $d \cdot x$. The coefficients *b* and *d* are model parameters and are in contrast to the population size *x* time independent. They are called relative birth and death rates to distinguish them from the absolute number of births *B* and deaths *D*. In the Forrester diagram this dependence of the birth rate *B* respectively the death rate *D* on the level variable *x* and the respective model parameters *b* and *d* is represented by information flows (Fig. 5). These information flows form two feedback loops.

In reality, of course, the situation is far more complicated and neither the relative birth nor the relative death rates remain constant over long periods. This can be taken into account by replacing the constants by auxiliary variables, which in turn depend on other system components (Fig. 6). This couples the differential equation for

the human population with other differential equations, hereby constituting a complex system [11]. The resulting complex system in its entirety can exhibit completely different behaviour than any of its individual parts does in isolation. The «World model 2" is in fact a system of 5th order, i.e. formed by five complicated, coupled ordinary differential equations containing many non-linearities (Fig. 13 in the Annex).

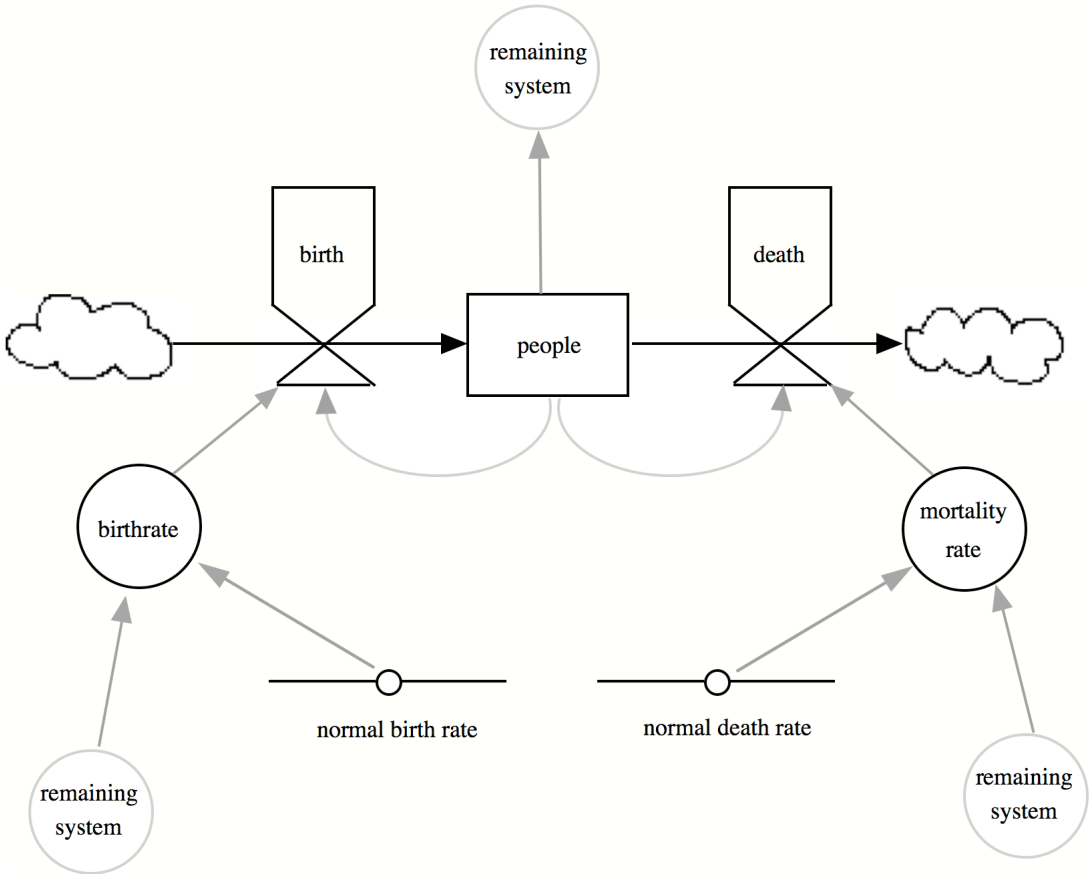

Fig. 6: Excerpt from the Forrester signal flow diagram of the *World model 2* modelling growth and decline of the human population (by Forrester, 1971, 1972; see also entire diagram in the Annex I).

System dynamics emphasizes the importance of **feedback loops** and recommends to analyze signal flow diagrams for their presence (closed signal flows, see e.g. Fig. 5 positive feedback from x to B and back to x). However, such an analysis is only of limited value, since in meshed feedback loops (Fig. 13) allow no longer for a clear classification into negative-stabilizing or positive-destabilizing feedback loops as this is possible for simple feedback loops (Fig. 6, 13). In meshed feedback loops some system element can be simultaneously part of a positive as well as a negative feedback loop and the overall effect may then be positive or negative, depending on the actual relative strength of the counteracting influences.

Forrester signal flow diagrams cannot be mapped to mathematical equations in a unique manner. For example the differential equation dx/dt = x/b - x/d would be also equivalent to the graph of Fig. 5. Therefore, system dynamics, despite advantages such as its lucidity, comes with a considerable number of drawbacks and deficiencies and cannot be generally recommended for modelling (see also Cellier & Fischlin, 1980). In particular it is also limited to the continuous-time formalism, i.e. modelling is constrained to systems of ordinary differential equations. Moreover, system dynamics was always strongly linked to a particular simulation language, i.e. DYNAMO and more recently STELLA, which invite unfortunately the skipping of the step of the explicit formulation of the mathematical equations.

While modelling a complex system such as the *World model 2* arises often the need to introduce so-called non-

[11] See, in particular, the signal flow diagram of the entire "World model2" in the Annex I (Fig. 13)

linearities. Nonlinearities are functions f(x), which do **not** satisfy following condition

$$f(a\cdot \vec{v}_1 + b\cdot \vec{v}_2) = a\cdot f(\vec{v}_1) + b\cdot f(\vec{v}_2)$$ (Definition of linearity, v = variable vector)

E.g., in the *World model 2* we find a non-linear function that represents the dependence of the usage of natural resources from the material standard of living (Fig. 7):

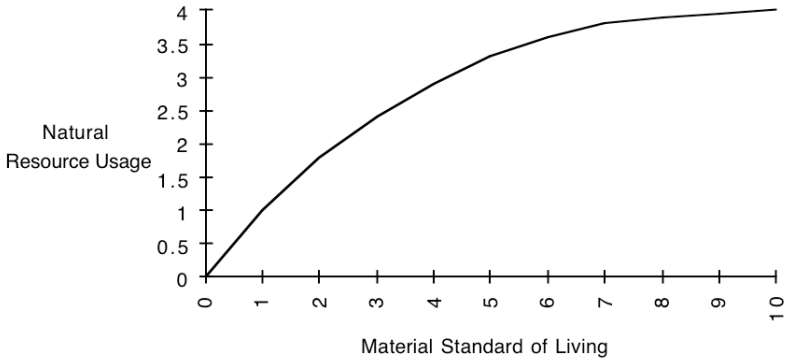

Fig. 7: Usage of natural resources as a function of material standard of living as used in *World model 2* .

Sometimes such a function can be described analytically or can be derived from analytical considerations. For example, physics tells us that we can describe in an electrical system a diode by an exponential function, while in the Lotka-Volterra predator-prey model

$$\dot{x}_1 = a\cdot x_1 - b\cdot x_1\cdot x_2$$ (x_1 = Number of prey animals)
$$\dot{x}_2 = c\cdot x_1\cdot x_2 - d\cdot x_2$$ (x_2 = Number of predator animals)

the nonlinear term $-b\cdot x_1\cdot x_2$ in the first equation can be justified with the argument that the number of prey will decrease the faster, the more predators are present (e.g. as long as many prey animals are present, the likelihood remains high that a predator encounters its victim, leading to a faster depletion of the prey population etc.).

While modelling complex systems it often occurs that a non-linearity cannot be formulated analytically. For example, the "World Model 2» contains a quantity capital investment, which is expressed as a function of the material standard of living, i.e. capital investment = *f*(material standard of living). How can we formulate such a relationship? For complicated relationships we may end up having to combine several analytical non-linear functions, which would lead to expensive computations during simulation or otherwise considerable numerical difficulties or even numerical error accumulation.

One remedy is to describe the nonlinear function using simply a dense table of values with coordinates defining the wanted function, called a **table function**. This approach is particularly handy in cases where one has only discrete measurements available that define the relationship.

During simulation one is likely to need values for which there is no corresponding entry in the table of values. **Interpolation** or **extrapolation** is then a means to find values that are missing, in the simplest case using straight lines**.** While linear interpolation is well defined and results only in the difficulty of a discontinuous derivative of the wanted function, extrapolation may be less well defined. The simulation language of System Dynamics, DYNAMO, offers two approaches: One is to retain the last function value beyond the range of the tabulated values for the independent variable (see the example below). A second is to extrapolate along the last interpolation line using the first or last, respectively, two entries from the value table.

Thus, the aforementioned non-linear dependence of natural resource usage = *f*(material standard of living) (cf. Fig. 7) is substituted for a value table together with means of interpolation for value pairs missing in-between and possibly extrapolation for values beyond the domain of the value table (Fig. 8):

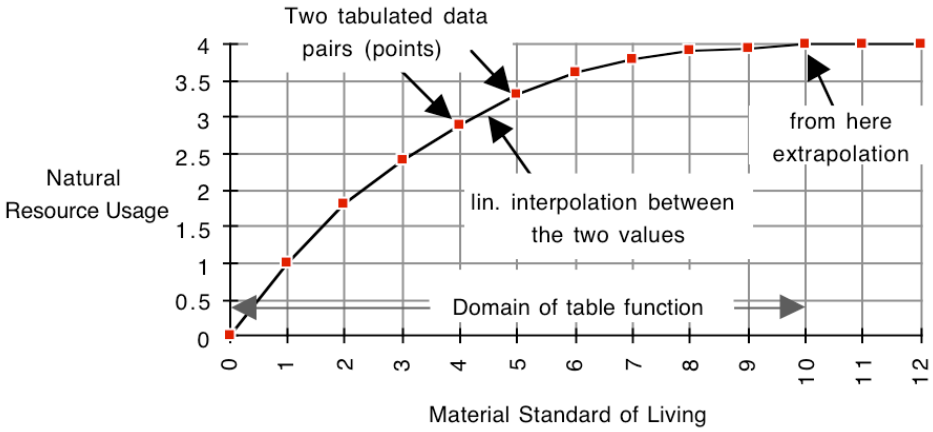

Fig. 8: The non-linear table function used by the *World model 2* representing the relationship between natural resource usage and material standard of living. Note, that the simulation model needs only the coordinates defining the red square points (■) that were derived from statistical data. Remaining function values are then calculated by the simulation software using linear interpolation (and possibly linear extrapolation, —).

The manner by which non-linearities are taken into account in a model may critically affect the simulation results[12]. In particular note that greatest errors may result in case of frequent, but undetected extrapolations, due to a mismatch between the domain for which the table function is defined and the actual domain into which the model values typically fall.

You can influence the temporal behaviour of an autonomous deterministic model system in general only by modifying the values of its model parameters or initial values. The latter is not possible in case of the *World model 2* . The reasons are firstly that the initial values have to use the values of the year 1900 and secondly the model has to reproduce as accurately as possible the past temporal evolution of the human population from 1900 up to the present. The only possibility to affect the behaviour of the model is to alter **values of model parameters** (note that the coordinates defining a table function may also be considered model parameters).

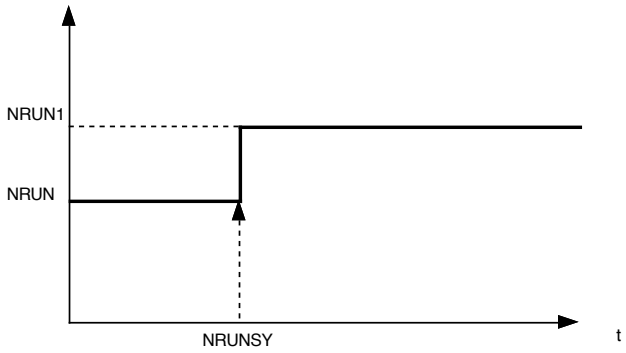

Fig. 9: A policy intervention in the *World model 2* is done by a discrete step, i.e. the value of the model parameter NRUN (Natural Resource Usage Normal) switches from value NRUN to value NRUN1 in the switching year (NRUNSY). In the original model the switching year is 1970. In the simulation model offered with this courseware the user can freely change both NRUN1 as well as NRUNSY.

World model 2 offers means to influence the future, not the past, by so-called switches (see Fig. 9). This switch allows a human user to intervene in the world affairs starting with the switching year (SY). This gives the user means to formulate better policies that would eventually lead to a desirable future development of humankind according to the users values. This is accomplished by changing values of a few selected parameters such as the

12 We were first not able to reproduce the published simulation results, since there was an error in the simulation language DYNAMO which Forrester and his team originally used. Only by reproducing the very same error could we reproduce the original results, i.e. we had to use another extrapolation method than the one described in the original code.

efficiency by which one uses natural resources or implements birth control. These changes are assumed to occur abruptly in a specific switching year, by default 1970[13]. An example is shown in Figure 9 for the parameter NRUN (rate of usage of natural non-renewable resources). Before the switching year NRUNSY the simulation model uses the default value NRUN, after year NRUNSY the user altered value NRUN1.

The standard behaviour of the *World model 2* (standard run), whereby the spectacular collapse of the world's human population in the 21st century occurs (Forrester, 1971), was simulated using unchanging parameter values. This means that for each model parameter that can switch the same value is used before and after the switch year 1970. In other words: World politics stay the same and are continued till the end of this century, a business as usual scenario. Exactly as this was the case with the original model (Forrester, 1971), those "normal circumstances" are specified by default in the simulation model coming with this courseware. Moreover, you can easily implement deviations from the business as usual policies by adjusting model parameters[14]. For example, a **new policy** of birth control can be implemented by setting the birth rate BRN1 to a lower value than the one valid for the past, i.e. BRN. Consequently with the switching year BRNSY fewer children would be born while other policies remain the same. Is this sufficient to improve the fate of humankind? Forrester (1971, 1972) has followed a similar approach and has postulated a possible remedy “towards a global equilibrium” that avoids the population collapse. Please go ahead, dear reader! - Well begun is half done! The simulation of the computer model will give you answers swiftly and perhaps you can design at least in the model world a small earthly paradise. Fortunately, in contrast to the bitter reality, no real human lives are at stake in the computer simulations!

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13 Forrester hat obviously no difficulties to imagine that the results of his studies would immediately alter world policy, what indeed was the case for a limited period of time. Whatever importance one may assign to the following historical events, it is a fact that the price of gold did rise immediately after the publication of the study «Limits to growth» (Meadows *et al*., 1972) and that an era of a new awareness of environmental problems was launched. The latter is manifested in the founding of UNEP (United Nations Environmental Program), the formation of the "Club of Rome", the emergence of widely recognized mottos such as "Limits to Growth" or "qualitative growth", and the founding of the International Institute for Applied Systems Analysis (IIASA) in Luxenburg near Vienna etc.

14 A complete list of all editable model parameters can be found in the Annex.

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3. Program description

The courseware provides an interactive simulation program. It allows to execute simulation experiments with the simulation model *World model 2* in any time domain and changing interactively parameter values freely. Simulation results are shown in form of graphs and tables.

The courseware was realized using the simulation environment *ModelWorks* (Fischlin & Ulrich, 1988; Fischlin et al., 1994). Some options of *ModelWorks* normally available have been omitted intentionally. E.g. neither the integration method nor the initial values of the state variables may be changed. On the other hand, all functions that are crucial to reach the learning goal are readily available: Among those are the interactive simulation, the ability to modify parameter values or to control a graphical or tabular representation of the simulation results (monitoring). For details, the user refers to the *ModelWorks* description (Fischlin *et al*., 1994).

Like any *ModelWorks* model definition program, the *World model 2* program remains in one of following three states always: *No simulation* (Model and program variables can be changed interactively), *Simulation* (The user can only abort or pause the current simulation), and *Pause* (The simulation is temporarily halted, e.g. to study tabulated results or change parameters). Fig. 10 shows the different program states with the associated menu and window commands, and also the commands, which permit a state change (grayed out menu or window commands are inactive and can not be invoked by the user / menu and window commands shown in black are active and can be freely invoked in any order at any time by the user).

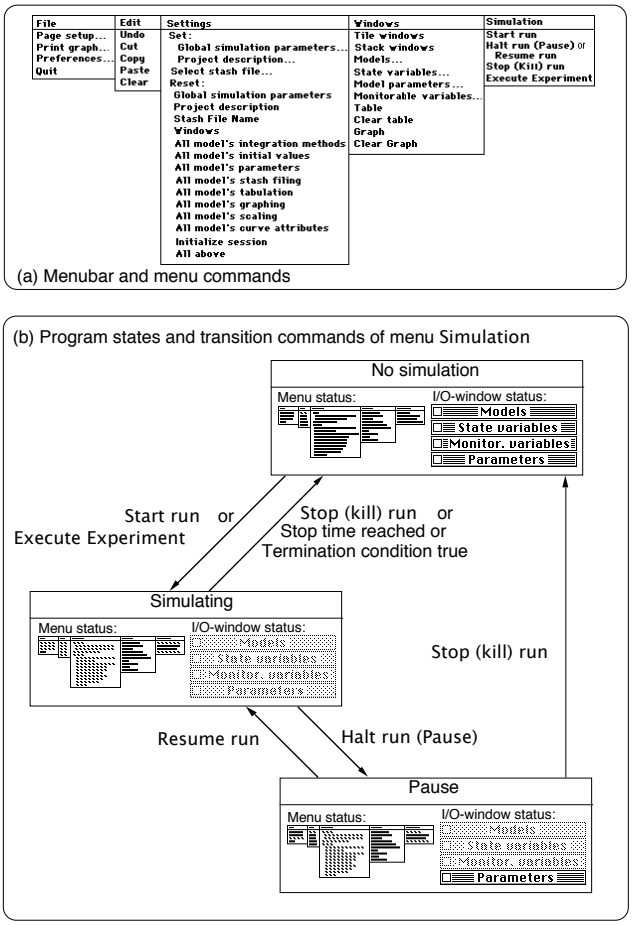

Fig. 10: Interactive user interface of *ModelWorks*: The simulation environment can only be in one of the following three states: In the state *No simulation* where most editing is done, e.g. setting of initial values, parameter values or choice of graphical representations. The state *Simulation* is entered during a simple simulation run or a simulation experiment consisting of several runs. In this state user actions are restricted to abort the simulation or pause it temporarily. In state *Pause* the values of RTC (Run Time Changeable) model parameters can be changed. Moreover, the simulation can be continued or aborted. From each state it is possible to quit the simulation environment.

4. Using the courseware program (User manual)

4.1 Tutorial

This section contains step-by-step instructions on how to work with the courseware program as needed to solve the problems (cf. section 5). It is recommended to instantly perform the described steps on the computer while reading this tutorial.

Assuming you are familiar with operating your computer and that you have successfully installed the courseware program as described in the distribution, you need first to launch the program *World Model 2*, typically by double-clicking its icon. A screen similar to the one shown in Fig. 11 becomes visible. The window *Model parameters* lists all editable model parameters and the window *Monitorable variables* lists all system elements that can be displayed graphically or tabulated, regardless whether that element is a state, auxiliary or output variable. The other two windows will be used to display simulation results.

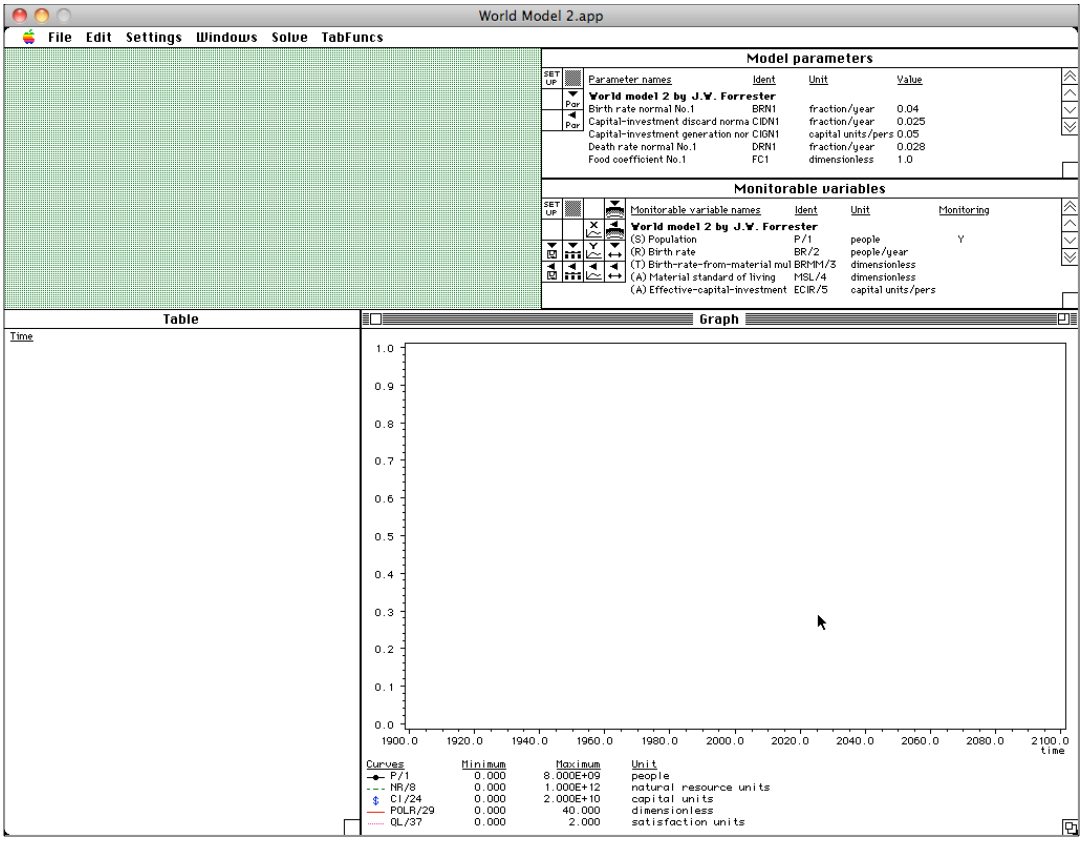

Fig. 11: Startup screen of the courseware program *World Model 2* (Mac OS X variant)

Best start by executing the standard simulation run. Choose in menu *Simulation* the command *Start Run*. If not already open, the window Graph will be opened, where you can track the fate of humans and other monitored variables. The curves are named with the very same abbreviated identifiers Forrester originally used (Forrester, 1971). **In the annex you find a list of all these system elements, their names (identifiers), meaning, and unit.** For the actual values see the program. First, notice that all curves reach or are at a maximum followed by a decline towards the year 2100. Limited growth! Watch in particular what happens to the world population P. It reaches its peak around 2020 and then collapses. What causes this drastic collapse in which billions of human beings die? To explore this we will try to plot the world population together with the birth and death rates.

Activate the window *Monitorable variables*. This can be accomplished by either clicking into the window title or by choosing in menu *Windows* the command *Monitorable variables*. You see now the first part of the list of all the variables, which can be monitored. Scroll to make the rest of the window content visible by clicking on

the scrolling icons at the top right corner. Listed are the five state variables (S, cf. Fig. 2), their rates (R) and all the auxiliary variables (A, cf. Fig. 13). The system elements are numbered as originally published (Forrester, 1971) and according to the order in which they are listed in the Annex I. All elements have a unique, abbreviated name (identifier), which prefixes its number from which it is separated by a slash, e.g., NR/8. The window also shows by default the unit, as well as its monitoring settings. Any variable to be plotted on the ordinate of the graph window shows a Y, any to be tabulated in the table window a T in the column *Monitoring*.

To get the wanted graph we need first to get rid of all **superfluous curves**, e.g. NR/8 would only distract us. Click its row and make sure it is inverted. From now on we call this an activated monitoring variable. **You find in the upper left corner of the window a panel of thirteen quadratic buttons.** Generally, a **facing down triangle** ▼ means **"Change the activated item"**and a **left-facing triangle** ◀ means **"reset the activated item to the value of the standard run"**. Click on the button Y. Confirm that the Y the column *Monitoring* for NR/8 has now disappeared. The effect will be that in the next simulation run NR/8 will no longer be monitored graphically, i.e. no such curve will appear in the graph anymore. Note, the button Y actually toggles the graphing. Click it once more, and the Y should appear again. Click it a last time to really remove it from the graph and repeat this procedure for CI/24, POLR/29, and QL/37. Now, only the population P shows still a Y. Proceed similarly by activating the birth and death rates BR/2 and DR/10: Activate the corresponding rows and click on button Y.

Start another simulation run. You can see that population growth is slowed down by a rising death rate, not a declining birth rate. Return to the original state by first clicking on the all gray button **select all** ▒, which will activate all monitoring variables, note, even the ones not visible. If you now click the button with the left-facing triangle ◀ ("reset"-button), you reset all monitoring exactly to what you had initially when you performed first the standard run. If you have made further changes, say in other windows too, it may be handy to use even a more comprehensive resetting technique: Choose menu command ***Reset all above*** from menu ***Settings.*** To reset really everything, including table functions, you need in addition to choose also menu command ***Reset all*** from menu ***TabFuncs***.

Forrester believed, as mentioned earlier, that world politics can be altered and that Earth's fate can effectively be changed. To deviate from the business as usual course change the values of the editable model parameters[15] (Fig. 9). Lets say we wish to strengthen birth control, then the relevant model parameter is BRN1. All editable model parameters have the suffix '1 ' at the end of their names, e.g. BRN1 compared to the default value used before the switching year, i.e. BRN. Remember, in the standard run all values are the same, e.g. BRN1 = BRN. Thus to intervene and implement birth control, simply decrease the value of BRN1 (BRN1 < BRN).

How to change an editable model parameter? Suppose we believe that recycling and efficient resource usage would make a difference. To implement the corresponding policy we need to reduce the **parameter** NRUN1 from 1.0 to 0.25. To accomplish this in our program, activate first the window ***Model Parameters*** **(**click on it or choose menu command **Model Parameters** in menu **Windows)**. Then activate NRUN1 and click on the button with the downward-facing triangle in the top left corner. A dialog window appears, where the new value can be entered. As a general rule, it is important to document your changes! The Annex I contains a form that helps you to keep track of your changes. That form illustrates its use by describing the standard run in the top row. Now write down the change you just made, e.g. by documenting it with "NRUN1 = 0.25" in the second row fo the form. Then, most importantly, sketch your expectations before you launch a new run! Only once you formed an opinion of the possible outcome run the simulation with the new value for NRUN1. Surprise, the crisis becomes still larger! Did you expect this?

Are you interested in what happens beyond 2100? Note that Forrester and his team (Forrester, 1971) seem not to have performed such an experiment, but *World Model 2* lets you easily explore this. Choose from menu ***Settings*** the command ***Set global simulation parameters.*** A dialog window appears in which you can increase the **Stop time for simulation**, say from 2100 to 2300. You may also wish to increase the monitoring interval to speed up the simulation, say to 10.0 (years). Note, merely changing the monitoring interval does not affect the results.

Note some curves such as QL/37 (material standard of living) or POLR/29 (pollution) reaches values outside the ones shown in the graph. Let us change the scaling. Activate window ***Monitorable variables*** and activate QL/37. Click on the button with a downward-facing triangle over a double arrow, the ***Set Scaling*** button ↕. A dialog window appears in which you can enter new scaling values. Set the new maximum (*Max*) for QL/37 to 15.0. Rerun the simulation and confirm that you can now see all of the curve for QL/37. The world's population

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15 Model parameters you can modify to implement a change in policy are the birth and death rates (BRN1, DRN1), natural resources usage (NRUN1), food coefficient (FC1), pollution (POLN1), and the economic growth determining capital-investment generation and discard (CIGN1 and CIDN1). For more details, see the list in the Annex I.

fluctuates enormously, not pleasant times to live! Merely reducing the usage of natural resources is obviously not a real solution, although this might be an important step in the right direction.

This run is worth-documenting and calls for some interpretation. Did it match your expectations? If not, be not irritated and embrace the opportunity for learning by searching for an explanation! Write down your thoughts in the last column of the form, no matter how vague or hypothetical they are. You are likely to profit later from these notes when you can compare several runs. It is therefore highly recommended to document all further simulation runs in a similar manner!

World Model 2 uses table functions extensively for the many complicated non-linear relationships it contains. Look e.g. at how the birth rate is varied by other influences at any given moment: The model contains seven different modifying factors that affect it (Fig. 13, table functions influencing birth rate BR)! Remember, any missing values, e.g. if such a factor reaches a value that falls between two values tabulated in the table function, then the missing value is calculated by linear interpolation between the nearest coordinates (cf. chapter 2.2, especially Fig. 8).

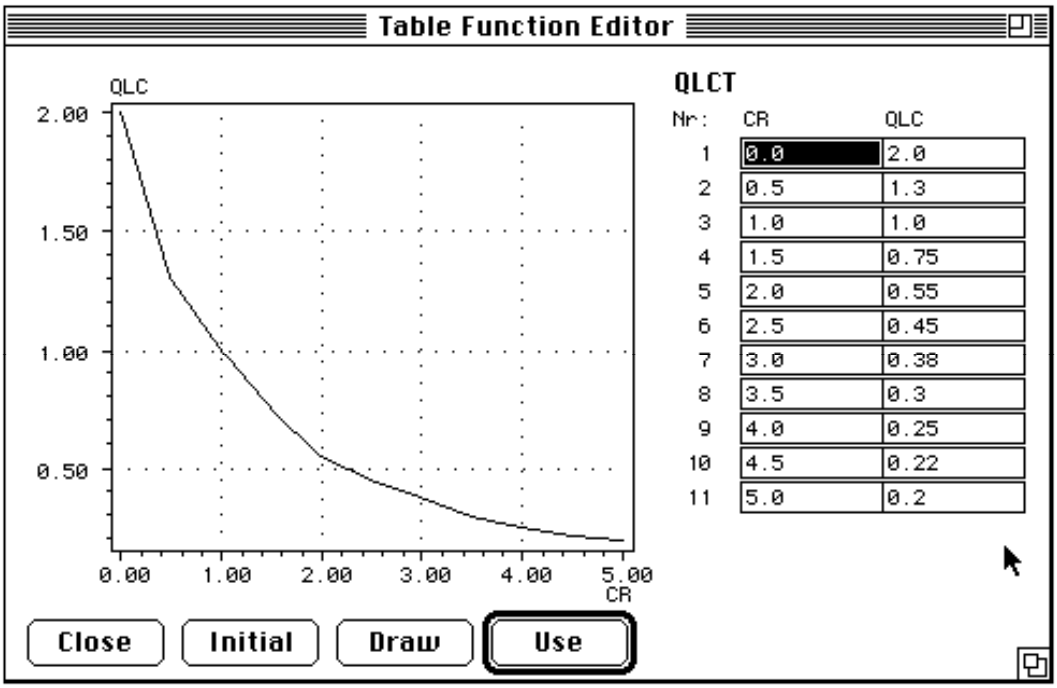

Fig. 12: Editor for table functions, shown here for the table function QLCT: The graph shows QLC (quality of life from crowding) vs. crowding ratio CR (population density).

Similar to the editable model parameters, these table functions can also be modified. Choose command ***Edit*** from menu ***TabFuncs***. A window appears where you can select the table function you wish to edit[16]. Confirm your choice by clicking button *OK*. Now another window opens (Fig. 12). To the left you see a graphical representation of the table function, to the right the value table of the coordinates. The left column of this table contains the independent x-values, here CR (crowding ratio, CR/15), the right column the dependent y-values, here QLC (quality of life from crowding, QLC/39). Use the tabulator key or click directly into a field holding a value to edit it. Update the graphical representation by clicking the button ***Draw*** (You may stumble over following restriction: The x-values must be in ascending order, and the y-values must not exceed or fall below internally defined limits, or you would risk a simulation model that could no longer be solved). Alternatively you can grab a point in the graph on the left side and drag it to another value.

Clicking on button ***Use*** saves all edits and assures the new table function will be used in all subsequent simulations. Click button ***Initial*** any time to forget most recent edits and return to the original values.

16 Identifiers of the table functions are formed from the identifier from the dependent auxiliary variable to be interpolated suffixed by the letter "T", e.g. the table function for auxiliary variable QLC is named QLCT (Fig. 12).

Button *Close* closes the window. In case you should have forgotten to first click button *Use*, don't worry, you will be asked whether you wish to retain or discard your edits, press buttons *Yes* or *No* accordingly. Choose menu command ***Reset*** from menu ***TabFuncs*** to reset an entire table function and return all its values to those initially contained in the value table as used in the standard run. Again when you use this menu command, a window appears where you need first to select the table function you wish to reset. Be warned, once you confirm your choice with *OK*, the selected table function will be reset completely (not revocable). You can even reset all table functions by choosing menu command ***Reset all*** from menu ***TabFuncs***.

By now you should have familiarized yourself sufficiently with the most important features of this courseware program, having made you fit to answer the problems from section 5. Note the simulation environment *ModelWorks* on which the courseware program *World model 2* is based offers many more features and means than introduced here can tackle considerably more complex systems. Visit the home of RAMSES[17] http://www.sysecol.ethz.ch/ramses for further information.

Have fun and lively discussions!

4.2 Reference (by menu commands)

FILE

Page Setup: Sets the paper size, the magnification and other settings needed for printing.

Print Graph: Prints the graphics window on the connected printer(s).

Preferences: Specify modes of the simulation environment.

Quit: Quit the program.

EDIT

Undo: This command is generally not available.

The following commands are relevant only for the window *Graph*:

Cut: Copies first the current graph into the clipboard before clearing it**.**

Copy: Copies the current graph into the clipboard.

Paste: Pastes the content of the clipboard into window *Graph* (successful only if the clipboard actually contains graphical content) (can be used e.g. to represent the same graphic with different aspect ratios).

Clear: Clears the current graph.

SETTINGS

Set global simulation parameters: Retrieves an inputs form in which the following values can be changed:
- Simulation start (*Start time for simulation)*
- Simulation end (*Stop time for simulation)*
- Length of the integration step (*Integration step*)
- Step length of the output on the graphics and in the table (*Monitoring interval*)

Set project description: Opens a dialog window in which you can enter a header, footer, and/or remark strings to be shown in graphs when printing. Use the check boxes *Use in Graph* to specify whether the header and the comment should also be shown on screen in the window *Graph*.

[17] Research Aids for Modeling and Simulation of Environmental Systems

The following data and information can be written onto the *stash-file* (check the corresponding check boxes):

- *Models*: Names of all models and *Global simulation parameters* currently in use
- *State variables*: Initial values of all state variables
- *Model parameters*: values of all model parameters currently in use
- *Monitorable variables*: Information on all monitorable variables
- *Graph*: Current graph as resulting at the end of a simulation run
- *Table functions*[18]: Information on all table functions incl. their value tables currently in use

Any program that can read text files can read the stash file. Graphical output can only be interpreted correctly by programs, which can fully read the RTF format, e.g. Microsoft Word®.

Select stash file: Specify the name and location of the so-called stash file, a file holding your monitored output. Note, stash files are written in the rtf format and can document your simulation runs fully. A stash file will not only store the results, but also contain sufficient information to precisely repeat a simulation experiment (for details see ModelWorks 2.2, Fischlin et al., 1994).

Reset: Reset all configurations, values, window objects etc. of the *World Model 2* back to their initial condition at program start.

WINDOWS

Tile Windows: Arranges the windows on the screen so that they do not overlap and are positioned side by side. Depending on the screen size, the windows may become rather small.

Stack Windows: Stacks the windows in an overlapping manner. Windows become larger, but content is partly obscured.

Model Parameters: Opens the window to inspect or edit the model parameters.

Monitorable variables: Opens the window to inspect or edit all monitoring variables, i.e. all system elements that can be plotted, tabulated, or written to the *stash-file*.

Table: Opens the window *Table* showing values of system elements set for tabulation (T).

Clear Table: Deletes the contents of the window *Table*.

Graph: Opens the window *Graph* showing curves for the system elements set for plotting.

Clear Graph: Deletes the curves in the graphics window.

SIMULATION

Start run: Starts a simulation run.

Halt run (Pause): Temporarily halts (pauses) a simulation run. In the resulting state windows can be viewed, repositioned, and model parameters can be changed (see Fig. 10).

Resume run: Resume the previously halted/paused simulation run. This command is only available (active) if the program is in state *Pause* (see Fig. 10).

Stop (Kill) run: Stops (aborts) the currently executing run. This command is only available (active) when the simulation program is in state *Simulation* or *Pause* (see Fig. 10).

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[18] Optionally available when at least one model uses a table function, which is the case for *World Model 2*

TABFUNCS (TABLE FUNCTIONS)

Edit: Opens first a window to select an individual table function and once the selection has been confirmed by pressing button *OK* the actual editing window is opened. It can be used to make changes to the selected table function (cf. 4.1 Tutorial).

Reset: Opens a window to select a table function (compare command *Edit*). Once the selection has been confirmed by pressing button *OK* the selected table function will be reset in its entirety to the initial values.

Reset all: Reset all table functions to their initial values.

Show window: Brings the editor window for table functions into the foreground. This command is inactive if no editor window is open for a table function.

4.3 Print or store current screen (screen dump)

Macintosh only: Command(⌘)**-Shift-3** (all pressed simultaneously)[19]**:** Creates a file named "Screen #" (# means a unique digit). This file can be printed with a drawing program (e.g. *GraphicsConverter*) or later inserted into a documention of your simulation experiments.

4.4 Cited references

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19 This option is only available on black and white screens, or on color screens set to black and white-mode (Set the number of screen colors in the control device "Monitors" in the desk accessory "Control panel").

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